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USAF SKID RESISTANCE PROGRAMS - A STATUS SUMMARY

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March 1975

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A STATUS SUMMARY

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This technical report was submitted to satisfy the requirements of Project 5549 by the Landing Gear and Mechanical Equipment Division, Directorate of Airframe Engineering, Deputy for Engineering, of the Aeronautical Systems Division, Wright-Patterson AFB, Ohio 45433.

This final report has been reviewed by the Information Office (OI) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This report has been reviewed and approved for publication.

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This report is a status summary of the USAF Skid Resistance Programs. Numerous programs have been conducted within the USAF and by joint USAF, FAA, and NASA agreements. Although much time and money have been expended, much more work is necessary before making a firm USAF operational commitment. Pavement grooving appears to be the best deterrent to aircraft hydroplaning, but must be reviewed in a cost effective manner and at best is a long term solution. The AFCEC Skid Resistance and Hydroplaning Potential Runway

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Evaluation Program is excellent and is a short term solution, but in itself cannot correct runway deficiencies but only point out the most critical ones. The method of predicting aircraft stopping distance derived in Combat Traction II, Phase II is very promising but requires additional analytical verification and clarification along with flight testing.

PREFACE

This is a status summary of USAF Skid Resistance Programs as directed by AFSC PD5549-2-73-80, 26 Jun 73.

The context of this report is a compilation of many technical reports and program briefings. The assistance of the applicable managers and engineers on these many projects has been appreciated. The assistance of AFCEC/DL (Capt J. Williams) has been greatly appreciated and the recent Skid Resistance Report Draft (Reference 5) has been quoted extensively.

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SECTION I

INTRODUCTION

With the introduction of jet aircraft into the United States Air Force (USAF) inventory, the operational difficulties of stopping and maintaining directional control on slippery (wet, icy, and snow covered) runways has increased to the extent that work was mandatory to research this phenomenon and to propose solutions. Because of similar commercial problems, the Federal Aviation Administration (FAA) also began research programs in conjunction with the National Aeronautics and Space Administration (NASA). This commonality henceforth manifested itself into numerous joint USAF-FAA-NASA programs.

The purpose for this report is to briefly summarize, past, and present, skid resistance related programs that required USAF resources and to recommend a logical, economical approach to bring all efforts to a reasonable end. The conclusions summarized are taken from the appropriate references without interpretation and without USAF confirmation of their correctness. There is no inference that conclusions summarized herein are still valid. Narratives, though, will be provided when a disagreement on conclusions has led to additional research.

SECTION II

PROGRAM SUMMARIES

1. Overview

Figure 1 is a flow chart showing the chronology and interrelationships of the many skid resistance programs undertaken by the USAF. All work started as a result of a joint NASA-British Ministry of Technology Skid Correlation Study in 1968. As a result of this, the USAF became active and initiated Project Combat Traction, later called Combat Traction I. This particular program highlighted the USAF operational difficulties and resulted in three primary avenues of USAF work. One area of research dealt with trying to increase the traction on runways by altering the pavement macro-texture (Pavement Grooving, Runway Surface Groove Configuration Improvement, and Porous Friction Surface Evaluation). The second area was to evaluate and categorize USAF runways with respect to their skid resistance and hydroplaning potential (Concrete Traction and Runway Skid Resistance Evaluation). The third, and last avenue sought to develop a system that could be utilized to reliably predict aircraft ground performance, i.e., primarily stop distance (Combat Traction II, Phase I; Combat Traction II, Phase II; and Combat Traction II, Phase II Extended). The Wet Runway Aircraft Control Project and F-4 Braking Test Program deal primarily with the effects of hardware and techniques on stopping performance.

The remainder of this section will contain the detailed objectives, work accomplished, and conclusions of these aforementioned programs.

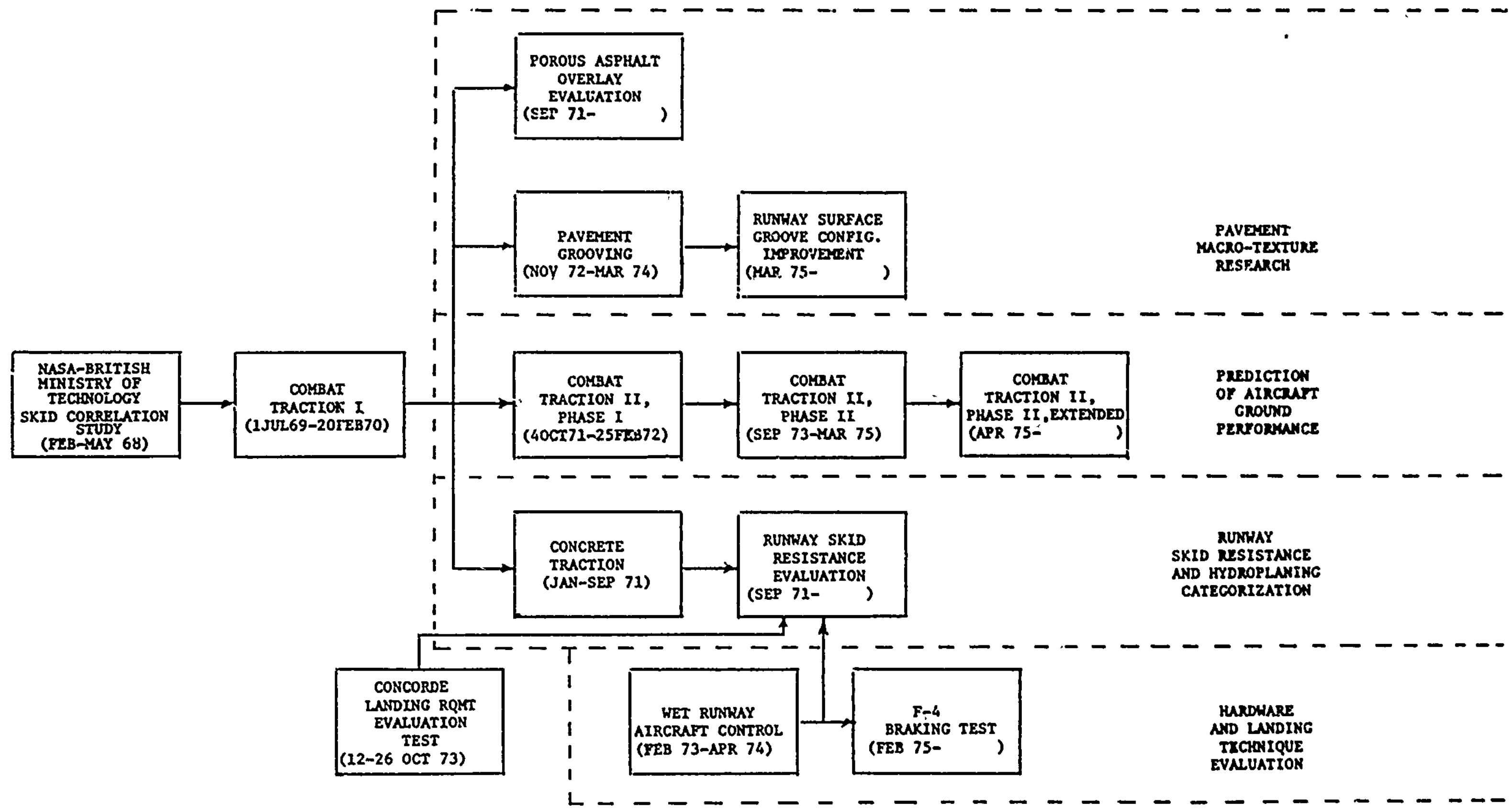

FIGURE 1. PAST AND PRESENT USAF SKID RESISTANCE PROGRAMS

2. NASA-British Ministry of Technology Skid Correlation Study

A flight test correlation program was conducted on the landing research runway at NASA Wallops Station to study the degree of correlation existing among braking friction data obtained by twenty-one different highway vehicles and braking trailers and both a McDonnell Douglas F-4D jet fighter (testing Feb-Mar 68) and a Convair 990 jet transport (testing Apr-May 68). Nine different runway surfaces were tested under wet, puddled, and flooded pavement conditions by aircraft with ground speeds up to 135 knots and by ground vehicles with speeds up to 70 miles per hour. The aircraft stopping distances were derived by "piece-wise" addition of numerous aircraft runs braking completely through the nine test section track. By altering the brake application velocity at the onset of the track, numerous "delta velocity vs. delta distance" plots were formulated and subsequently used. The runway condition reading (RCR) method of predicting aircraft stop distance was also used to ascertain the validity of the James Brake Decelerometer (JBD). The details of this study are documented in Reference 1 and an excerpt discussing the ground vehicles used is presented in Appendix A. The USAF participation in this program consisted of personnel to operate, and the supply of, certain ground vehicles and an unofficial monitoring of the testing.

The primary objectives of this program were:

a. Determine the degree of correlation in friction measurements obtained by highway vehicles and braking trailers currently used in the United States and Great Britain.

b. Study the operation of present systems which attempt to correlate aircraft stopping performance with ground vehicle braking action. Additionally, the merits or failings of these systems during wet pavement operations will be addressed.

c. Recommend the most advantageous system to reliably, and accurately predict aircraft stopping performance.

The conclusions made by NASA, based upon flight test results were:

a. Good correlation exists between instrumented highway vehicles and braking trailers, regardless of braking mode, when vehicle path-clearing or water-film thickness variations on the pavement surface are minimized.

b. The ASTM bald-tread vehicle tire is much more sensitive to pavement slipperiness factors such as speed and water film thickness than is the ASTM rib-tread tire.

c. The F-4D and 990 demonstrated good correlation in defining the state of slipperiness existing during tests on all pavement sections.

d. The RCR system cannot predict a possible hydroplaning situation on the runway nor can it be used for estimating aircraft stopping capability.

e. The Swedish skiddometer, or other techniques utilizing ground vehicle friction coefficients, can determine whether a hydroplaning situation exists but cannot be used to predict aircraft stopping capability. This capability of predicting hydroplaning situations also affords the prediction of aircraft directional control in crosswinds.

f. The concept of predicting aircraft stopping distance by correlating the aircraft wet-to-dry stopping distance ratio (SDR) to the diagonal braked vehicle (DBV) wet-to-dry SDR appeared favorable but would necessitate further tests to quantify.

An evaluation conducted by British personnel additionally concluded that:

a. A fair degree of correlation exists between the Miles Trailer and Mu-Meter at 55 and 40 mph, respectively, with the F-4D and 990.

b. The one by one-fourth by one-fourth inch grooving at least doubled the friction coefficient over the ungrooved surface. Reducing the pitch from one inch to three-fourths inch did not appear to make a difference.

c. The open textured asphalt test section was as effective as one-eighth inch grooved asphalt or concrete.

d. The concrete surfaces, whether grooved or ungrooved, were in general slightly lower in friction than asphalt.

e. Small holes radially located in the tire tread appeared to increase the developed friction significantly on slippery surfaces but was not as significant on grooved surfaces.

3. Combat Traction I

From 1 Jul 69 to 20 Feb 70, NASA and the USAF (ASD/ENFL, 4950th, and AFWL/DEZ) cosponsored a flight test program involving a C-141A, a DBV, and a JBD operating from fifty runways in the United States and Europe. The conditions of these runways included dry, wet, flooded, slush-, snow-, and ice-covered surfaces.

The objective of this, as stated in Reference 3, are:

a. Assemble a priority list of USAF runways requiring corrective measures to prevent skidding/hydroplaning accidents.

b. Determine the optimum runway surface for USAF use.

c. Establish and validate a means for predicting aircraft stopping distance for various surfaces, etc., using a ground vehicle as a means of assessing surface condition.

d. Investigate a water-depth warning system or other measuring system.

The conclusions of a joint NASA-USAF (ASD/ENFL) team, as documented in Reference 4, are:

a. The RCR system used by the USAF is not an adequate method for predicting aircraft stopping distance on a wet runway, but it could be used to conservatively predict stopping distance on ice- and snow-covered runways.

b. A DBV can be used to predict aircraft stopping distance and crosswind limitations for wet, ice-, and snow-covered runways and can be used to measure runway slipperiness.

c. Grooved pavements and porous asphalt surfaces were the most effective surface treatments investigated in alleviating surface flooding and wet runway slipperiness.

d. Aircraft stopping distance generally increases with increasing water depth on the runway.

In addition to these conclusions, a list was formulated displaying the aircraft SDR, DBV SDR, and RCR dry-to-wet ratio as determined on each runway. There was no attempt to assemble a priority list of runways requiring corrective measures.

As can be noted by comparing the conclusions and objectives, this program indicated additional avenues of research rather than to specifically answer the questions originally posed. For this reason, additional programs were planned to meet these objectives.

4. Concrete Traction

As reported in Reference 5, skid resistance measurements were made by the USAF (AFCEC) on 75 runways at 48 Air Force installations between Jan-Sep 71. Measurements were made on the primary and secondary touchdown areas and on the interior portion of the runway.

The primary objective of this program was to determine the slipperiness of USAF runways.

The validity of test results was questionable since adequate control of water application was not achieved.

5. Combat Traction II, Phase I

The objective of this flight test program was to determine if a relationship exists between the Boeing 727-100 and Douglas DC-9 and the Mu-Meter and/or DBV. The program was conducted under a joint FAA, NASA, USAF agreement. The USAF participants were ASD/ENFL, AFFDL, 4950th, and AFWL/DEZ. The results of the seventy-nine 727 landings conducted from 4 Oct 71 through 16 Oct 71 are presented in Reference 6 and Reference 7 contains the results of the eighty-four DC-9 landings conducted from 12 Feb 72 through 25 Feb 72. Neither of these two documents, however, contain conclusions. The primary cause that firm conclusions were not made was a disagreement between FAA, NASA, and the USAF on data reduction techniques, methods of data display, and data interpretation.

These test results do serve as a basis for the AFCEC Runway Skid Resistance Program (see Section II.6). Analysis of the 727 results from six different runways indicated that the brake control system allowed wheel lock-ups to occur over a wide range of operating conditions. Wheel lock-ups occurred during all wet stops on smooth Portland cement concrete (PCC) pavements resulting in excessively long stop distances. The data showed that, for the 727, wheel lock-ups were likely to occur when runway conditions corresponded to a DBV SDR of 2.05 or greater and a Mu-Meter reading of 0.47 or less (See Reference 5). Testing of the DC-9 ascertained that no wheel lock-ups would occur, but excessive stop distances could be encountered which exceeded the wet stop distance prescribed by Federal Air Regulations (FAR) 121.195. (See Reference 5.)

6. Runway Skid Resistance Evaluation

During 1970, AFWL was tasked by AFSC to develop a skid resistance system that would accurately evaluate runway skid resistance/hydroplaning characteristics. The system developed is detailed in Reference 8. These initial tests were begun by AFWL/DEZ in Sep 71 and in Jul 73 the responsibility was transferred to AFCEC. To date, fifty-four USAF runways have been evaluated and the results given in Reference 5.

The primary objective of this program is to categorize USAF runways according to their slipperiness and recommend, to Hq USAF/PREE, the runways requiring the most immediate corrective action. All of the conclusions to date are given in Reference 5. The most noteworthy are:

a. The AFCEC Skid Resistance Survey Program can determine runway skid resistance characteristics and runway hydroplaning potential. However, aircraft stopping distance cannot be accurately determined using measurements obtained from the Mu-Meter or DBV.

b. Hydroplaning potential is probable for some aircraft whenever the DBV SDR exceeds 2.0 and the Mu-Meter reading is below 0.5.

c. The DBV and Mu-Meter are suitable measurement devices for assessing relative skid resistance characteristics and complement one another.

d. Regardless of pavement material, the majority of touchdown rubber deposit areas exhibit hydroplaning potential.

e. The majority of burlap drag finished PCC runways exhibit some degree of hydroplaning potential.

f. The NASA DBV and USAF DEV assess the pavement slipperiness slightly differently than one another.

g. The NASA "grease smear method" cannot predict hydroplaning potential when the texture depth is greater than 0.016 inch but can assess relative hydroplaning potential below this value.

h. Improving pavement texture and cross slope appear to be the most effective means for alleviating hydroplaning potential.

7. <u>Porous Asphalt Overlay Evaluation</u>

The objective of this work being accomplished by the USAF (AFWL/DEZ) is to evaluate porous asphalt overlay as anti-hydroplaning surfaces for use on asphaltic concrete runways. The original concept for the Porous Friction Surface (PFS) was developed and used in Europe, but received little or no attention in the United States until recently.

In Sep 71, seven different porous asphalt test strips were constructed on a taxiway at Kirtland AFB (Albuquerque International Airport) and in Sep 72, a PFS was constructed on a runway at Pease AFB. The test surfaces consisted of a slurry seal, a grooved slurry seal, three test sections of Palmer Pavetread with various groove patterns and two PFS. Details of the construction of these surfaces and the resultant evaluations can be found in References 13 and 14. References 15 and 16 are reports presently in publication that deal with PFS and other research undertaken by AFWL. The primary conclusions made in References 13 and 14 were:

a. All surfaces indicated that a significant reduction in hydroplaning potential can be obtained.

b. There was no apparent freeze-thaw damage to any of the surfaces.

c. Marshall test specimens of porous asphalt exhibited a loss in stability as a result of cyclic freezing and thawing but did not exhibit this same tendency as damp-freeze specimens.

d. Monitoring the surfaces under trafficking for six months, it was noted that there was:

(1) Excessive loss of aggregate on the asphalt slurry.

(2) Good bonding between Pavetread and concrete.

(3) Unacceptable reaction between Pavetread and asphaltic joint sealer.

(4) Unacceptable bonding between Pavetread and asphalt pavement.

(5) Good performance from porous asphalt prepared with rubber.

(6) Excessive loss of aggregate on porous surface with emulsified asphalt.

e. The porous asphalt hot mix (with latex rubber) resisted 500 passes with the C-130 tire and 500 passes with the F-4 without showing any signs of distress in the form of raveling or shoving.

f. The performance of the overlay material under the simulated loadings was considered superior to the asphalt slurry, porous asphalt cold mix, and Pavetread overlays.

8. Pavement Grooving

This program was conducted from Nov 72 to Mar 74 and was a joint FAA-USAF (ASD/ENFL/SMK1) contracted effort with Lockheed-California Company. The details of this program are documented in Reference 10.

The objectives of this program were:

a. Determine when tire cutting (chevron cutting) occurs during the landing maneuver.

b. Develop a laboratory simulation method by which new and retread tires can be qualified for service on various grooved runway pavements.

c. Provide data which will facilitate development of pavement grooving configurations which minimize the problem of tire cutting and spin-up load effects.

The significant conclusions of this effort were:

a. A laboratory technique was developed from which test results show good correlation with tire damage experienced during actual airplane landing operations on grooved pavements.

b. The laboratory test results show that tire chevron cutting occurs, if encountered, at the instant of pavement contact.

c. The severity of tire chevron cutting is less on dry grooved one by one-fourth by one-fourth inch asphalt, two by one-fourth by one-fourth inch concrete, and one by one-eighth by one-eighth inch concrete surfaces than on a one by one-fourth by one-fourth inch ground concrete surface.

d. Rounding or chamfering the surface edges of a one by one-fourth by one-fourth inch grooved concrete surface does not appear to reduce tire damage.

e. The measured dry friction coefficient for a grooved one by one-fourth by one-fourth inch concrete surface is significantly higher than on a one by one-eighth by one-eighth inch or two by one-fourth by one-fourth inch grooved concrete surface.

9. Runway Surface Grooving Configuration Improvement

At the time of writing this report, these tests had not begun. This is a FAA program to be conducted at Lakehurst NAS under a FAA-United States Navy (USN) agreement. There is also a FAA-USAF (ASD) interagency agreement whereby the USAF will supply available hardware.

The primary objectives of this program are to:

a. Demonstrate that the Lakehurst facility will accurately recreate operational tire chevron cutting experience.

b. Determine if a groove shape change will alleviate tire chevron cutting and, if so, which shapes are advantageous.

c. Using the groove shapes found above, vary the groove spacing, banding, etc., and determine the friction/hydroplaning effects.

d. Study and analyze the groove patterns (shape, spacing, banding, etc.) from a cost effective standpoint.

The pavements to be grooved will be PCC and bituminous concrete using FAA/APS runway pavement specifications.

10. Combat Traction II, Phase II

This program is a continuation of the agreement between the USAF, FAA, and NASA that led to Combat Traction II, Phase I (see Section II.5). This is an analytical effort, contracted to The Boeing Commercial Airplane Company, that began in September 1973 and ended in March 1975. The details of this effort can be found in Reference 11.

The primary objectives of this particular program were:

a. Identify the parameters that have an effect on aircraft stopping performance.

b. By the use of an analog-brake control system simulation of the Boeing 727, 737, 747, and the C-141A and F-4D determine the factors that significantly affect aircraft stopping performance.

c. Develop a model for predicting aircraft stopping performance.

d. Formulate the criteria for a system to predict aircraft stopping distance.

e. Based on the above criteria, evaluate the DBV and Mu-Meter.

f. State the methodology to be used to forecast aircraft stopping performance.

g. Recommend follow-on work.

The primary conclusions of this program were:

a. Dimensional analysis technique can be successfully used to express the braking phenomenon.

b. Experimental data from airplane braking distance sensitivity study is needed to develop a prediction model for a particular aircraft.

c. With proper information, the aircraft braking distances can be predicted within reasonable tolerances.

d. The most important requirements for a vehicle to accurately measure tire-runway interface friction are the selection of a proper tire and a faithful reproduction of the interface dynamics.

e. The existing ground vehicles, i.e., DBV and Mu-Meter, fail to meet the required criteria.

In addition to these conclusions, the generalized model to predict aircraft stopping performance was formulated (along with the particular equations for the Boeing 727, 737, 747 and C-141A and F-4D) and the criteria for an aircraft stopping distance prediction system was given.

11. Combat Traction II, Phase II Extended

This program is essentially a continuation of Combat Traction II, Phase II (see Section II.10) intended to carry on research started in that program. This USAF program is to begin in April 1975 and again to be a contracted effort between the Boeing Commercial Airplane Company and ASD/SMAA/ENFL, with monitorship and funding from AFCEC.

The primary objectives of this program are:

a. Develop a system to predict the friction available to an aircraft. An integral part of this is a tire model that can be used to correlate a vehicle tire friction capability to an aircraft.

b. Conduct an analytical study similar to the ones from Combat Traction II, Phase II on the B-52, KC-135, and F-111. This is intended to confirm the previous results.

c. Assure that the Friction Prediction Subsystem (FPSS), from objective a, is compatible with the Braking Prediction Subsystem formulated in the previous program and that the composite system, the Total Braking Prediction System (TBPS), is sufficient to predict aircraft performance.

d. Write a specification to permit procurement of the FPSS.

12. Concorde Landing Requirement Evaluation Tests

This was a FAA flight test program conducted with the assistance of NASA, the USAF (AFCEC), the Aerospace Industries Association (AIA, Air Transport Association (ATA), Airline Pilots Association (ALPA), Allied Pilots Association (APA), Canada Ministry of Transport (MOT), U. K. Civil Aviation Authority (UK-CAA), and French STAE. The vehicles tested during the 12 Oct 73 to 26 Oct 73 flight test program were a Lockheed L-1011, Boeing ~~727~~ 737, NASA DBV, USAF DBV, USAF Mu-Meter, Boeing Miles Trailer, and FAA Swedish Skiddometer. The details of these tests are given in Reference 9.

The primary objective of this program was to evaluate the Concorde landing requirement to ascertain if all facets of the requirement could be applied in a practical manner without overburdening the certification test program. The conclusions of this program are given in Reference 9. The FAA conclusions that reflect upon the USAF Skid Resistance Program are:

a. From a practical standpoint, there is no consistent, or precise correlation between the various ground vehicles.

b. Satisfactory relationships were established between aircraft SDR and the wet and dry friction coefficients from which wet stopping distances can be computed.

c. Further examination of alternate methods of comparing aircraft and ground vehicle relationships are indicated.

d. The DBV was shown to provide a reasonable relationship to the two aircraft tested and its results can be related to the aircraft effective wet braking friction coefficient.

It should be pointed out that this latter conclusion has been questioned by some of the program participants. To resolve this, the FAA has established a special task group to review all data and either confirm this conclusion or provide an alternative.

13. Wet Runway Aircraft Control Project (Rain Tire)

The project consisted of 164 landings with an F-4E (143 of which were in a wet test section) at Edwards AFB between January 1973 and September 1973 and 267 data points from NASA LaRC (252 of which were in a wet test track) between February 1973 and April 1974 (see Reference 12).

The primary objectives of this program were:

a. A main tire tread design modification that must yield at least a 25 percent increase in friction on wet surfaces with less than 25 percent decrease in tire tread life.

b. An anti-skid system improvement that must exhibit an increase in wet surface stopping efficiency with no decrease in system reliability.

c. A steering system change that would increase the directional control capability on wet surfaces.

d. Determine the effect on main tire spin-up characteristics as a result of touchdown sink rate.

e. Determine the effect on main tire spin-up and aircraft stopping distance as a result of 60 percent main tire wear.

The primary conclusions of this program are:

a. The BFG and USAF nose tires provide a significant improvement in cornering capability over the Standard.

b. The Sommer main tire provided significant improvement in both stopping potential (in general, more than 25 percent in available braking tire-ground friction coefficient) and cornering capability but degraded the tire structural integrity and possibly reduced the tire life.

c. The Mark III brake control system yields significant improvements in both stopping potential (at least 10 percent reduction from Mark II) and main wheel control.

d. It appears that main wheel spin-up time increases with decreasing touchdown sink rates.

e. A 50 percent worn Standard main tire will yield significantly longer stop distances than the new tire.

14. <u>F-4 Braking Test Program</u>

As a result of the Rain Tire Project recommendations (see Reference 12) and the decision to replace the F-4 anti-skid system, the F-4 SPO initiated a flight test program to be conducted at Edwards AFB. This program commenced in Feb 1975 with an anticipated 78 test points required.

The objectives of this effort are to:

a. Functionally verify the touchdown and crossover locked wheel protection features of the Mark III brake control system.

b. Provide flight manual landing performance data for the Mark III brake control system.

c. Determine the wet runway stopping performance degradation as caused by a 40 and 70 percent worn main tire.

d. Determine the main wheel spin-up characteristics when touching down on the rubber-coated portion of the runway.

e. Determine the optimum stick position (horizontal tail position) for landing rollout on wet runways.

f. Determine the magnitude of additional main landing gear loads if spoilers were utilized during landing rollout.

g. Determine the wet runway stop performance when using molded transverse groove main tires (Traction Tread).

SECTION III

CONCLUSIONS AND RECOMMENDATIONS

1. Conclusions

a. Runway grooving on Portland cement concrete pavements appears to be the best solution to reduce aircraft hydroplaning potential while the application of Porous Friction Surface with proper transverse slope appears to be the best solution for asphaltic concrete runways. The cost effectiveness of grooving would have to be investigated in view of the potential problem with chevron cutting of tires.

b. The technique utilized by AFCEC has satisfactorily categorized USAF runways according to their skid resistance and hydroplaning potential.

c. The method proposed by FAA to predict aircraft stopping performance is technically questionable and requires additional data review.

d. The method proposed in Combat Traction II, Phase II of predicting aircraft stopping performance has promise but requires additional analytical work and flight test verification.

e. Hardware improvements can be made to enhance stop performance but this performance improvement is limited and dynamic hydroplaning cannot necessarily be eliminated.

2. Recommendations

a. The Runway Surface Groove Configuration Improvement Program (FAA) should be monitored closely by the USAF.

b. The AFCEC Runway Skid Resistance/Hydroplaning Potential Evaluation Program should continue. Any refinements to this technique that simplifies the method, gathers additional significant data, or potentially facilitates a more thorough runway categorization should be made.

c. Further analytical work should be conducted to expand upon, and verify, the aircraft stopping performance prediction method proposed in Combat Traction II, Phase II and to devise a method to predict directional control performance on slippery runways.

d. An overall USAF program should be formulated to coordinate all efforts and a USAF organization assigned to manage and oversee this. This overall program would undoubtedly necessitate as yet unscheduled funding.

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APPENDIX A

DESCRIPTION OF GROUND VEHICLES USED IN NASA-BRITISH MINISTRY OF TECHNOLOGY SKID CORRELATION STUDY

APPENDIX A

The following six organizations operated two-wheel braking trailers during the skid correlation study: Bureau of Public Roads (BPR), Florida State Road Department, Tennessee Highway Research Program, Virginia Highway Research Council, General Motors Corporation (GM), Goodyear Tire and Rubber Company. All of these trailers conformed to ASTM Tentative Standard for Skid Trailers, ASTM Designation E 274-65 T.

Data were obtained for all of these trailers by braking either one or both of the trailer wheels to a full skid and recording ground speed and friction coefficients on direct-writing recorders. The General Motors braking trailer measured braking force rather than braking torque and thus had the additional capability of recording values of the transient peak friction coefficient as the test wheel was braked from a free-roll to a locked-wheel, or full-skid, condition.

The Pennsylvania State University Automotive Safety Research Program operated its single-wheel braking trailer during the skid correlation study. This trailer measures braking force and, like the General Motors trailer, records the complete friction-coefficient variation of the tire as it is braked from a free-roll to a locked-wheel condition. Thus both transient peak and locked-wheel friction-coefficient data can be obtained. The vertical load applied to the test wheel was also different from that applied to the two-wheel trailers. The ASTM specification calls for 1080 pounds of vertical load per tire. The load applied on the Pennsylvania State University trailer wheel was only 800 pounds.

The Federal Aviation Administration operated a three-wheel constant-slip trailer (Swedish Skiddometer) designed by the Swedish Statinvagininstitut. In this trailer, the centrally located test wheel is connected by a solid axle drive with appropriate universal joints to the two larger diameter outer trailer wheels. Thus the test wheel is forced to rotate at the same angular velocity as the outer trailer wheels. The ratio of test-wheel diameter to outer-wheel diameter is set such that the test wheel is forced to roll at a constant slip ratio of approximately 0.13. This slip ratio, which was determined by testing, usually produces a maximum braking friction condition on the test tire.

The B. F. Goodrich Tire and Rubber Company (BFG) and NASA operated diagonal braking automobiles during the study. The braking systems on the B. F. Goodrich sedan and NASA station wagon were modified by installing cut-off valves in the brake lines. These valves allowed one pair of diagonal wheels on each automobile to be braked while the opposite pair of wheels, unbraked and freely rolling, were free to steer or develop cornering or side forces for maintaining vehicle stability. This braking technique makes it possible for the test automobile to enter locked-wheel skids at high speeds on wet pavements and still maintain good directional control. Another useful feature of this technique is that diagonal braking automatically compensates for load transfer during brake application and one-half the vehicle mass is always braked. This technique simplified the computation of friction coefficients to simply subtracting the unbraked tire value of the vehicle deceleration from its braked value at a given ground speed and doubling the result.

The B. F. Goodrich diagonal braking sedan was equipped with a recording longitudinal accelerometer mounted at the vehicle pitch center and a trailing wheel for measuring ground speed. Outputs from both instruments were recorded on a direct-writing recorder. The NASA diagonal braking station wagon initially used a Tapley meter, which is a damped-pendulum maximum-reading accelerometer, to measure braking action during diagonal braking. Later instrumentation similar to that used in the B. F. Goodrich sedan was employed.

The United States Air Force, Federal Aviation Administration, NASA, and Ford Motor Company operated four-wheel braking automobiles during the study. The United States Air Force automobile will be described since it was the only vehicle to acquire a complete set of data on the research runway. A Tapley meter and a James brake decelerometer were mounted securely to the front floor of a 1966 station wagon by NASA. This automobile was driven by an officer-engineer from the U. S. Air Force, Wright-Patterson Air Force Base who was versed in the U. S. Air Force Runway Condition Reading (RCR) system. This system calls for an application of brakes hard enough to lock all four wheels at speeds of 20 to 30 miles per hour. The maximum reading of both the Tapley meter and James brake decelerometer was then recorded after each test brake application.

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